ACEE Int. J. on Civil and Environmental Engineering, Vol. 2, No. 1, Aug 2013

Urban Air Quality Modelling and Simulation: A Case Study of Kolhapur (M.S.), India

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***Abstract*— As a consequence of urbanization a phenomenal surge has been observed in the vehicular population in India, giving rise to elevated levels of traffic related pollutants like carbon monoxide, nitrogen oxides, hydrocarbons, and particulates in Indian urban centers. These pollutants can have both acute and chronic effects on human health. Thus air quality management needs immediate attention. Air quality models simulate the physical and chemical processes occurring in the atmosphere to estimate the atmospheric pollutant concentration. A variety of air quality models are available ranging from simple empirical models to complex Computational Fluid Dynamic (CFD) models. Air quality models can be a valuable tool in pollution forecasting, air quality management, traffic management and urban planning. This paper evaluates the performance of widely used Danish Operational Street Pollution Model (OSPM) under Indian traffic conditions. Comparison between predicted and observed concentrations was performed using both quantitative and statistical methods. OSPM was found to perform exceedingly well for the prediction of particulates whereas NO_2 predictions were poorly predicted.**

***Index Terms*— Vehicular Emissions; Air quality; Air quality models; Street canyon.**

I. Introduction

Hasty economic growth in the course of urban development is causing serious air pollution problems in many cities throughout India. A phenomenal surge has been observed in vehicular population in Indian cities leading to highest ambient concentrations in the congested streets [1].

As a consequence of urban development, along with energy, the transport sector has been the centre of attention during last decade. The transport sector in India consumes about 16.9% i.e. 36.5 million tonnes of oil equivalent (mtoe) of total energy. Among different types of motor vehicles, percentage of two wheelers has shown rapid growth and it constitutes 70% of total motor vehicles of India [2].

According to source apportionment studies conducted by Central Pollution Control Board (CPCB), India; in cities like Delhi, Kanpur, Bangalore, Pune, Chennai, Mumbai, transport sector contributes to more than 30% of the ambient air pollution. These contributions are either direct from vehicular exhaust or indirect through resuspension of road dust due to vehicular movement. Even in many of the two tier cities in India, traffic and inadequate infrastructure facilities are responsible for higher local air pollution levels [3]. The higher contribution of transportation sector to air pollution in India can be attributed to predominance of older vehicles in the fleet, inadequate inspection and maintenance; further improper traffic management system, road conditions, absence of effective mass rapid transport system and intra-city railway networks have aggravated this situation [4].

Considering the continual traffic growth and emissions and their impact on human health and urban air quality there is an urgent need for a regulatory framework for the management of traffic, air quality and emissions at local level, as well as at regional and national scales [5]. Air quality models can help to develop air quality management action plans and serves as an effective tool for improving air quality in urban centers.

Air quality models predict the dispersion and dilution processes of the pollutants in the atmosphere using the emissions, prevailing meteorological conditions and street configurations to determine the ambient air concentrations [6]. A variety of line source and street canyon models are now available, starting from simple empirical models to complex Computational Fluid Dynamic (CFD) models [7, 8, 9].

This paper discusses the current scenario of the transportation sector in terms of air pollution and reviews the air quality modelling studies conducted in India. Future scope for air quality modelling and simulation is also discussed.

II. Health Effects Of Traffic Originated Air Pollutants

Atmospheric pollutants can cause both acute and chronic effects on human health. CO is a suffocating pollutant which reacts with hemoglobin in the blood forming carboxy hemoglobin (COHb) and thereby reduces the oxygen carrying capacity of blood. Short-term exposure to high CO concentrations can cause an acute health impact [10]. Benzene compounds have a cumulative effect on human health. Long-term exposure to high benzene levels can cause risk of cancer. Oxides of nitrogen are responsible for both short and long-term health effects like altered lung function, respiratory illness and lung tissue damage [13].

Particle size is an important consideration because particles in certain size ranges have profound effect on human health. Fig. 1, shows the deposition of particles in the respiratory system. Smaller the size of the particle it is likely to penetrate deeper in the lungs. Particles greater than 100

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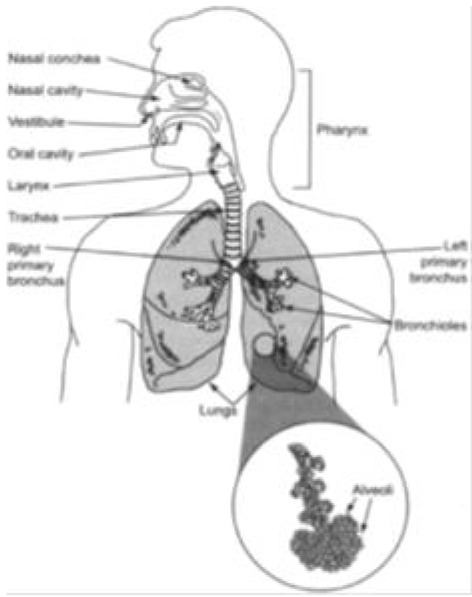

Figure 1. Respiratory Collection of Particles [11]

μm are typically not inhaled, while smaller particles, typically less than 4 μm, can interfere with oxygen gas-exchange in the lung alveolar region [14].

Respirable Particulate Matter (PM_{10}) and Fine Particulate Matter ($PM_{2.5}$) have been found to associate with increased mortality and asthma [15, 16]. Ultrafine particles (PM_1) can cause cardiopulmonary diseases, cardiovascular diseases, and respiratory diseases [12].

III. Description Of The Study Area

Kolhapur city is located in Maharashtra state (INDIA) at 16°42'N 74°13' Eÿþ/ 16.7; 74.22. It has an average elevation of 545 meters (1788 ft). The geographical area of the district is 7685 km^2. This research work concentrates on the study of a section of Station Road (Fig.2), which runs through the heart of Kolhapur city and comprises one of the busiest routes towards the city centre.

As street configuration and structures nearby affect the air flow and thereby influence dispersion and dilution processes within the streets. Table I presents details of street configuration.

Table I. Details Of Street Configuration

Length of the street	130 m
Width of the street	32.97 m
Average height of buildings	13 m
Orientation of the street	68^0 to the North
Height to Width Ratio (Aspect ratio)	0.4
Length to Height ratio	10

IV. Methodology

This section explains the experimental and computational methodology used to investigate and evaluate the performance of the employed air quality model. Fig. 3, presents an outline of steps necessary for air quality modeling study.

The study was divided into two major parts: air quality modelling and ambient sampling. Air quality modelling uses various dispersion models to predict the hourly concentration of pollutants in the street. Such model requires input data such as Traffic data, Emission factors, Meteorological parameters (ambient temperature, wind speed and direction, etc.) [17], Street geometry i.e. length and width of streets, Height of buildings, Angle between street and wind direction, etc., and background concentration of pollutants. Using the

Figure 2. Location of the study area

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mathematical framework dispersion models calculate the pollutant concentrations at desired receptor locations.

The second part deals with the ambient sampling and analysis to determine the pollutant concentrations in the street. Predicted and observed concentrations are used for statistical analysis of dispersion models validation. Results of this study can be used for assessing roadside air quality by providing predictions of present and future air pollution levels as well as temporal and spatial variations.

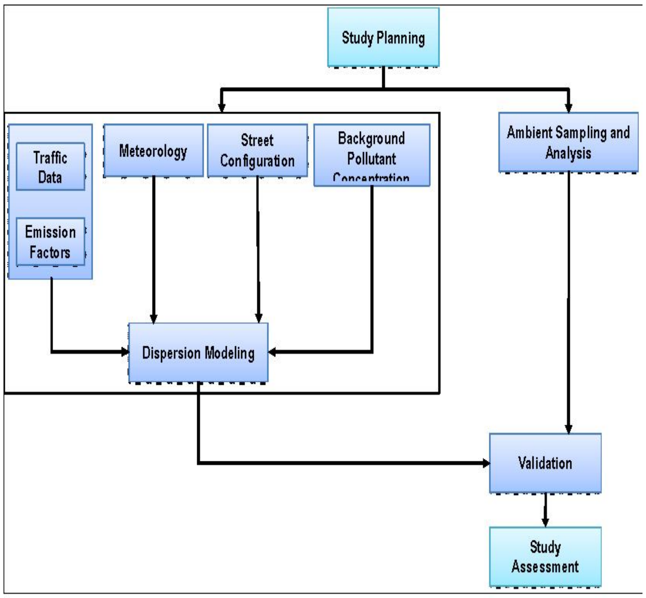

Figure 3. Framework for Air Quality Modelling Study

A. Operational Street Pollution Model (OSPM)

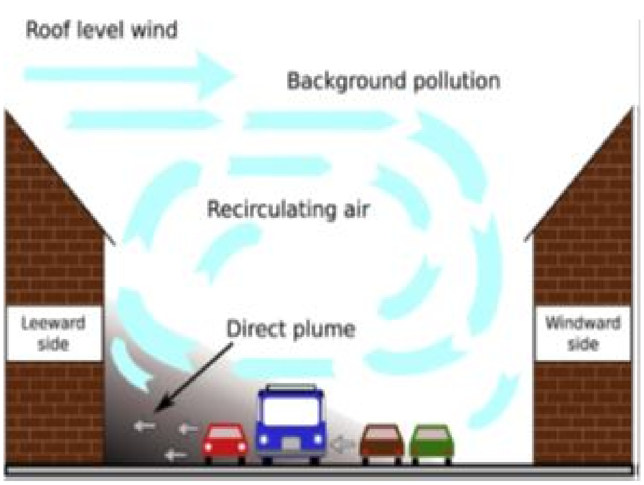

Figure 4. Schematic illustration of basic model principles used in OSPM

Operational Street Pollution Model [18] evolved from the Canyon Plume Box Model (CPBM). OSPM is a parameterized, semi-empirical model which can be used to calculate concentrations of vehicular pollutants on both leeward and windward sides of a street canyon. Fig. 4, illustrates the basic principles used in OSPM. OSPM calculates contribution from i) direct vehicular exhaust ii) recirculation of pollutant within canyon due to vortex formation and iii) background concentration [7]. OSPM uses Gaussian plume model to calculate direct contribution from vehicular exhaust whereas recirculation is modeled using a box model technique. OSPM models turbulence in the street considering wind turbulence and traffic induced turbulence [19].

The input data required by OSPM include: Traffic volume, Source strength, Meteorological data such as wind speed and direction at 10m height, Solar radiation data, Canyon geometry such as length, width and orientation of the street and height of buildings surrounding street and Background concentrations. The latest versions of OSPM can predict hourly concentrations for CO, NOx, Ozone, VOC, and Particulates.

B. Traffic Data

Air quality models require detailed information on traffic volume, fleet composition, and average travel speed. Traffic volume data are hourly average values of manual counts performed at selected street during the study period. Traffic counts were performed everyday during 1st December, 2012 to 31st January, 2013 and the time span chosen for study is everyday 9:00 to 13:00 (Morning) and 16:00 to 20:00 (Evening) to capture the peak hours.

C. Emissions

Vehicular emissions were calculated using the hourly traffic volume and the average emission factors. The source strength was computed for each of the pollutant as:

$$\mathbf{Q\ (g - km^{-1}hr^{-1}) = N\ (hr^{-1})\ x\ EF\ (g - km^{-1})}$$

In the present study, average emission factors were compiled from various literatures including regulatory agencies like Central Pollution Control Board (CPCB) and

Table II. Summary Of Emission Factors Used In The Study(G/Km)

Vehicle Category	NOx	SPM	PM_{10}
Two Wheelers	0.19	0.05	0.10
Three Wheelers	1.28	0.20	0.20
Passenger Cars (Gasoline)	0.20	0.03	0.10
Passenger Cars (Diesel)	0.50	0.07	1.00
Light Duty Vehicles	2.00	0.56	1.25
Heavy Duty Vehicles	6.30	0.28	2.00
Buses	12.00	0.56	1.50

research institutes like Automotive Research Association of India (ARAI), National Environmental Engineering Research Institute (NEERI), etc. A summary of chosen emission factors is provided in the table II.

D. Meteorological Data

Meteorological data for this research work is collected using an Automatic Weather Station (AWS) (Oregon Scientific, Model: WMR200) which provided with the

DOI: 01.IJCEE.2.1.2

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prevailing meteorological conditions at the measurement site. The meteorological parameters monitored include: Temperature, Wind speed (Rooftop level), and Wind Direction.

E. Urban Background Measurements

The background concentration of pollutants plays a vital role in urban air quality modeling. Rooftop measurement method is employed to determine the background concentration of pollutants under consideration namely PM_{10}, SPM and NO_2. Background concentrations were determined using High volume method. OSPM further requires background concentration of ozone as input, due to unavailability of resources for measurement of ozone a constant value of 21.15 ppb has been used for the calculations [20].

F. Ambient Sampling and Analysis

Measurement and monitoring for the selected traffic originated pollutants namely: Particulates and Nitrogen dioxide is carried out during the months of December 2012 and January 2013. Particulates concentration is determined gravimetrically using high volume method. Air is drawn through a size-selective inlet and through a 20.3 X 25.4 cm (8 X 10 in) whatmann filter at a flow rate of 1132 L/min. Particles with aerodynamic diameter less than the cut-point of the inlet are collected, by the filter. The mass of these particles is determined by the difference in filter weights prior to and after sampling. The concentration of SPM and PM_{10} in the designated size range is calculated by dividing the weight gain of the filter by the volume of air sampled [22].

Concentration of ambient nitrogen dioxide is determined by Modified Jacobs & Hochheiser Method [22]. Ambient nitrogen dioxide (NO_2) is collected by bubbling air through a solution of sodium hydroxide and sodium arsenite. The concentration of nitrite ion (NO^{-2}) produced during sampling is determined colorimetrically by reacting the nitrite ion with phosphoric acid, sulfanilamide, and N-(1-naphthyl)-ethylenediamine di-hydrochloride (NEDA) and measuring the absorbance of the highly coloured azodye at 540 nm [22].

G Statistical Analysis

Model performance was evaluated using statistical analysis. The statistical parameters used here includes: Index of agreement, Correlation coefficient, and Fractional bias as defined in table III.

IA value indicates the degree to which observed concentrations are accurately predicted by the model. In other words, it is a measure of degree to which the model predictions are error free [23]. Correlation coefficient (R), explains the degree to which fluctuations in observed concentrations are followed by fluctuations in predicted concentrations. It varies between +1 < R < -1, where ±1 indicating a perfect correlation and 0 indicating no correlation at all [24]. FB is a measure of agreement between mean concentrations and it ranges between +2 and -2 [6].

IV. Results And Discussion

A. Emission Rates from Automobiles

Fig. 5, shows the scale map of observed traffic during monitoring period. Two wheelers were observed to be dominating throughout the monitoring period with a percentage of 56% followed by passenger cars (29%). Light Diesel Vehicles (LDV) was observed to be minimum with a percentage of 2%. It is evident from the above distributions that two wheelers and passenger cars comprise predominant source of exhaust emissions and also mechanical turbulence in the confined urban environment.

Contribution to air pollution from automobiles is generated using traffic density and emission factors. The results obtained are shown in the Fig. 6. Emission rates are observed to follow the trend of traffic density in the street. As emission factor for NOx are higher, emission rates of NOx are observed to be dominating during the monitoring period.

Table III. Statistical Parameters

Index of Agreement (IA):	$IA = 1 - \frac{\overline{(C_{pred} - C_{obs})^2}}{\overline{\left(\lvert C_{pred} - \overline{C_{obs}}\rvert + \lvert C_{obs} - \overline{C_{obs}}\rvert\right)^2}}$
Correlation coefficient (R):	$R = \frac{\overline{(C_{obs} - \overline{C_{obs}})(C_{pred} - \overline{C_{pred}})}}{\sigma_{obs}\,\sigma_{pred}}$
Fractional bias (FB):	$FB = \frac{2\left(\overline{C_{pred}} - \overline{C_{obs}}\right)}{\overline{C_{pred}} + \overline{C_{obs}}}$

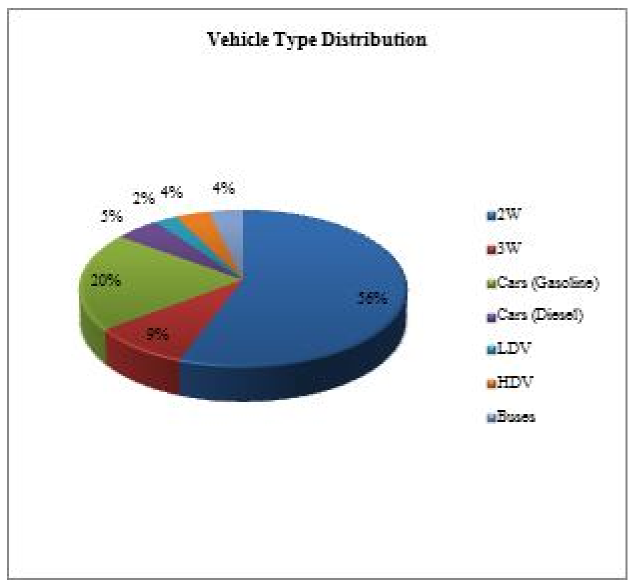

Figure 5. Scale map of traffic during monitoring period

B. Meteorological Data

The study was carried out during the winter season and average ambient temperature during the monitoring period was found to be 27.3^{0}C. Fig. 7, shows the variation in the temperature during monitoring period.

Hourly wind speed and direction data were collected at the monitoring site. Fig. 8, shows the windrose diagrams for

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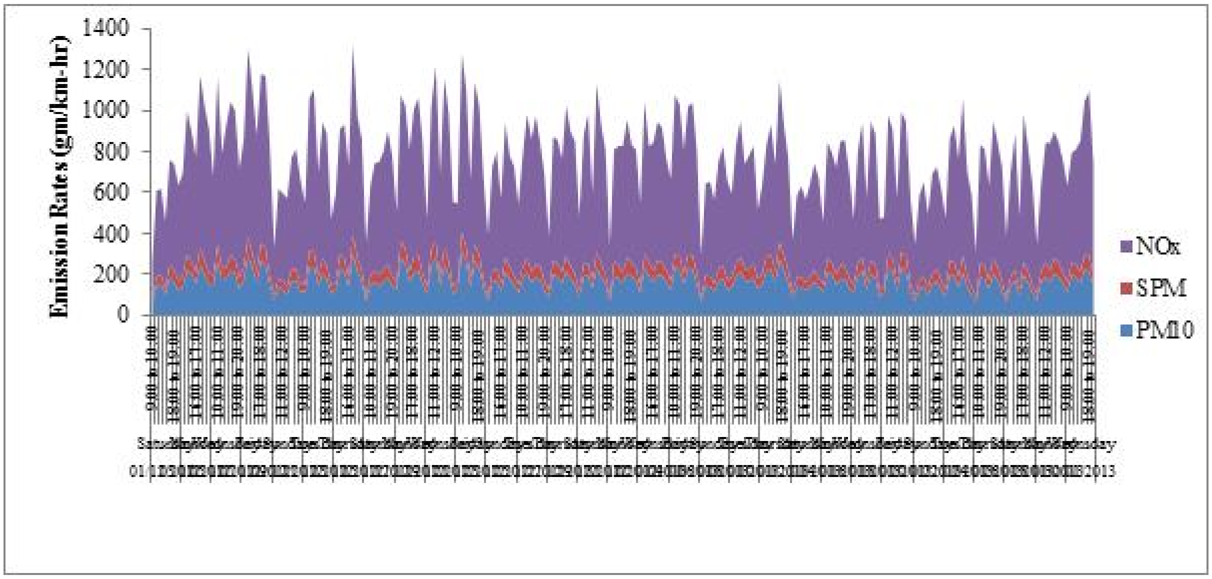

Figure 6. Emission rates from automobiles during monitoring period

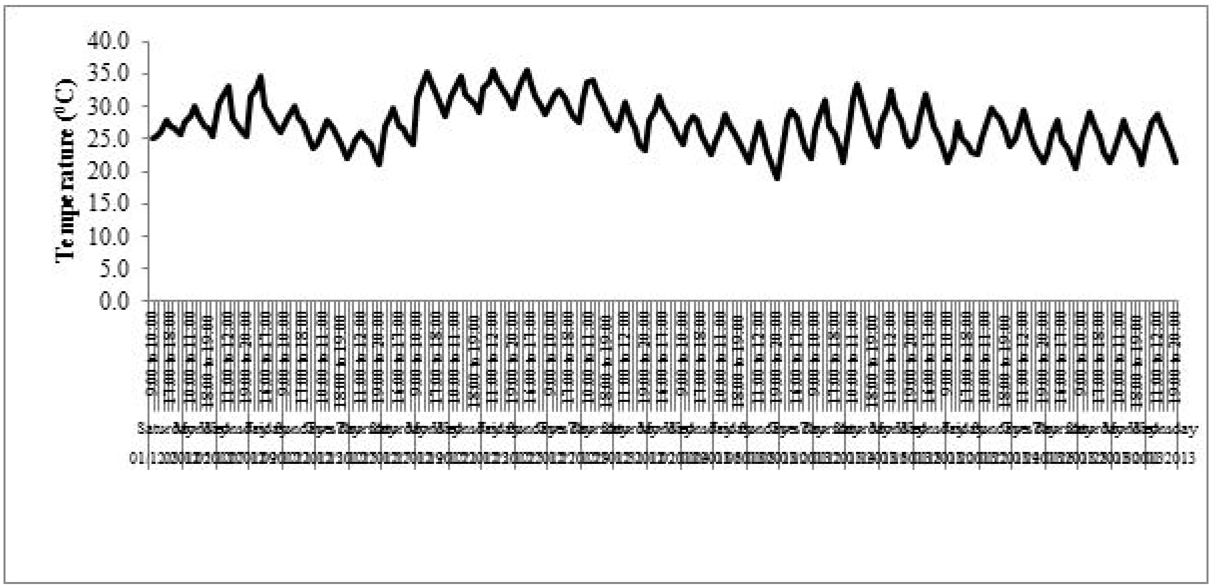

Figure 7. Trend of temperature during monitoring period

the monitoring site. It was observed that, North-Westerly (NW) winds predominate during the monitoring period. These prevailing wind flows are perpendicular or near-perpendicular to the street canyon axis.

C. Urban Background Measurements

As urban background measurements plays a crucial role in urban air quality modelling, providing hourly urban background air quality data is the greatest challenge. As discussed earlier rooftop measurement method was employed to determine the background concentrations of selected pollutants. Due to unavailability of resources for NO measurement, concentrations of NOx were determined mathematically assuming NOx/NO_2 ratio of 1.32 [20].

Fig. 9, presents variations in the background concentrations of the pollutants (PM_{10}, SPM, NO_2 and NOx). As chosen monitoring period was winter season, often a higher background concentration of pollutants were observed due to prevailing stable atmospheric conditions.

D. Air Quality Modelling

Air quality modelling involves assessment of traffic originated pollutants (PM_{10}, SPM, NO_2) at selected urban street canyon site, using Operational Street Pollution Model (OSPM). Air quality in street was monitored during the selected monitoring period and it is compared with predicted concentrations obtained with OSPM. Details on emission rates, Meteorological data, Street configuration, and urban background concentrations are used as input to the model in required units. Further for modeling NOx chemistry, a photolysis rate constant is taken $J_{NO^2} = 0.015\ s^{-1}$ and NO/NO_2 ratio=0.32 [20, 21].

It was observed that the models produce a mixed nature of predictions for different pollutants. When comparing concentrations on a day to day basis model was found to perform well for PM_{10} and SPM but for NO_2 predictions a poor

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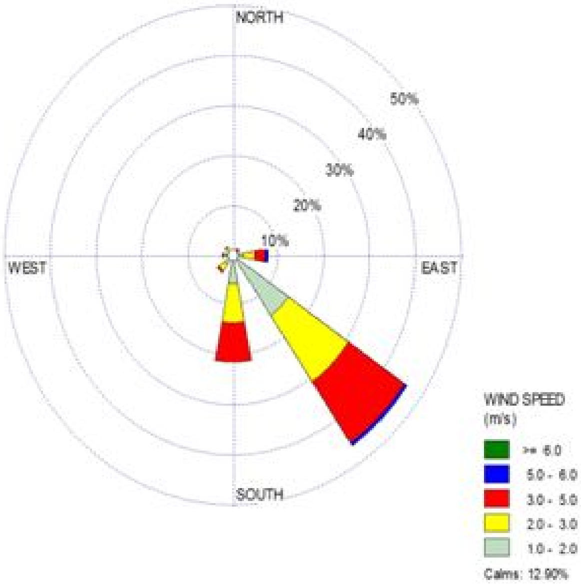

Figure 8. Windrose plot for study location during monitoring period

model performance was observed. Fig. 10, 11 and 12, shows the comparative performance of OSPM for modelling PM_{10}, SPM and NO_2 concentrations respectively.

OSPM was found to under predict PM_{10} concentrations but a good correlation was observed between predicted and observed SPM concentrations. The reason for under-prediction of particulates might be the emission factors considered in the study are purely based on exhaust emissions, no considerations has been given for inclusion of non-exhaust particulate emissions like tyre wear. Another additional reason might be the contribution of road side resuspended dust to particulate concentrations.

NO_2 values were observed to be over predicted throughout the monitoring period. The reason for over-prediction can be the use of higher NOx emission factors. Further a constant value of background ozone concentration is used to model NOx chemistry, due to unavailability of background ozone concentrations in Kolhapur area.

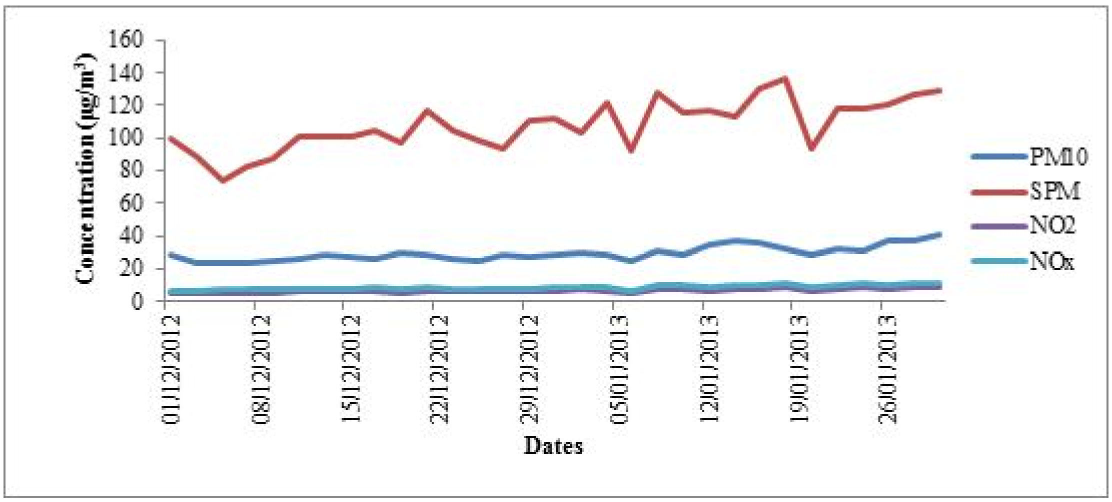

Figure 9. Variations in urban background concentrations during monitoring period

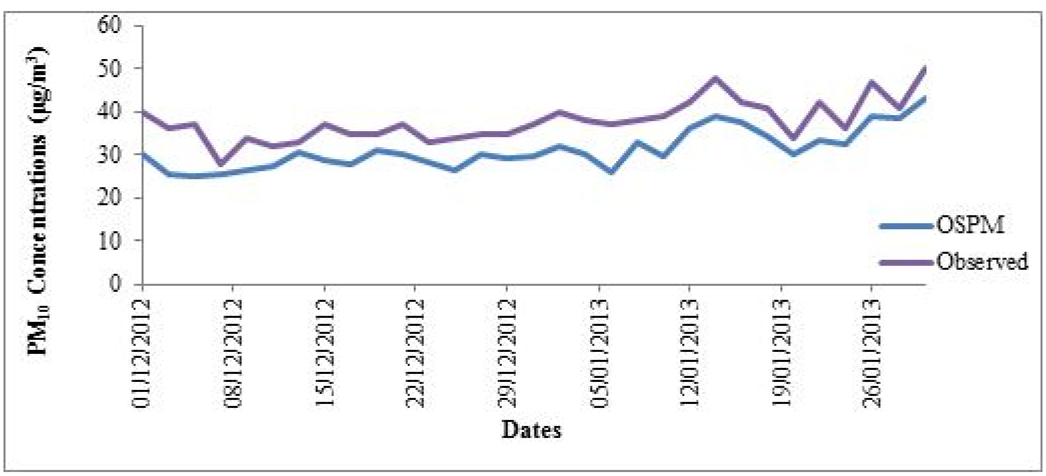

Figure 10. Comparison of predicted and observed concentrations for PM10

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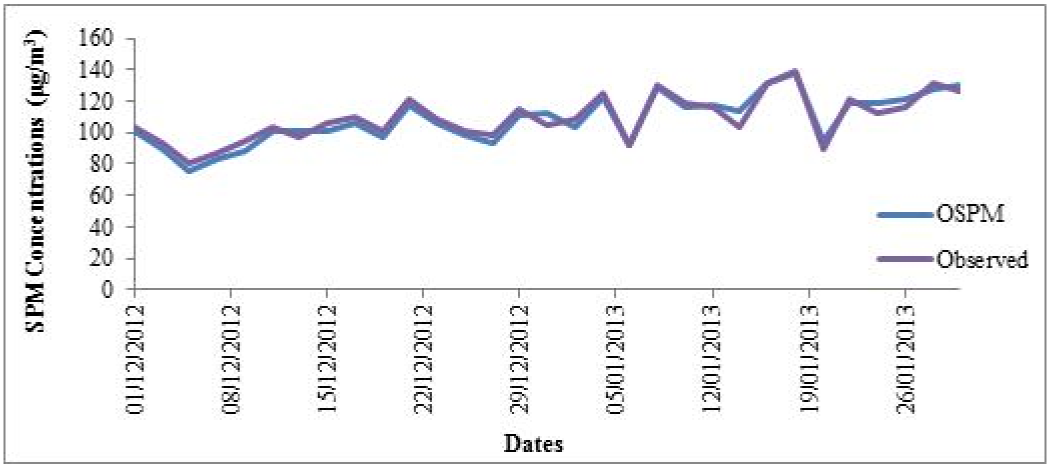

Figure 11. Comparison of predicted and observed concentrations for SPM

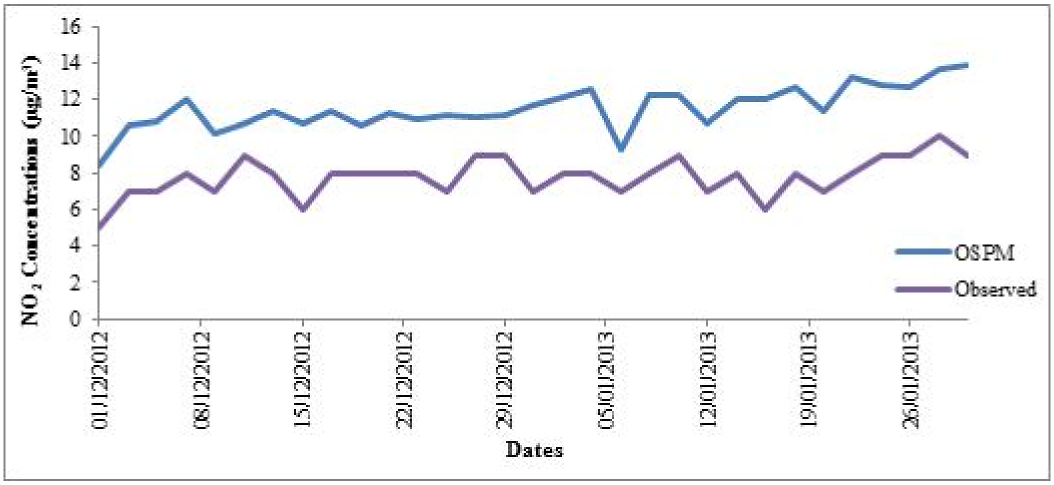

Figure 12. Comparison of predicted and observed concentrations for NO2

E. Performance Evaluation of OSPM

Statistical performance measures for monitoring period are tabulated in table IV.

TABLE IV. SUMMARY OF STATISTICAL PARAMETERS USED IN THE STUDY

	PM_{10}	SPM	NO_2
Index of Agreement (IA)	0.62	0.98	0.34
Fractional Bias (FB)	-0.19	-0.01	0.38
Correlation Coefficient (R)	0.85	0.96	0.64

High values of Index of Agreement (IA) were obtained for SPM and PM_{10} but IA value was observed to be lower for NO_2 suggesting better model performance for PM_{10} and SPM predictions than that of NO_2 predictions. Values of FB are -0.19 (PM_{10}), -0.01 (SPM), 0.38(NO_2) indicating that OSPM under predicts 19%, and 1% for PM_{10} and SPM respectively whereas 38% over predicts for NO_2 when compared to observed value. It can be observed that Correlation coefficients for 0.85, 0.96, and 0.64 for PM_{10}, SPM, and NO_2 respectively, reflecting good correlation between predicted and observed values of pollutants.

V. CONCLUSIONS

Automobiles are considered to be the primary source of urban air pollution. Pollutants from automobile sources are emitted near large number of people. As source – receptor distances are short and concentration can be high, which may affect health of the people adversely.

This paper evaluated the performance of OSPM for predicting concentrations traffic pollutants in an urban canyon. OSPM was found to simulate the concentrations of particulates better than NO_2 on short term basis. NO_2 concentrations were consistently over predicted by the model. Performance of the model can be further improved with more accurate emission factors and urban background measurements.

A major limitation of air quality modelling in India is unavailability of high quality databases. Regulatory agencies needs to strengthen the monitoring network as well as more number of pollutants like Carbon monoxide, Ozone, VOCs, needs to be included.

ACKNOWLEDGMENT

I would like to thank with deep sense of gratitude my

DOI: 01.IJCEE.2.1.2

guides Prof. Atul Ayare, Head and Associate Professor at Department of Environmental Engineering, KIT's College of Engineering, Kolhapur, Maharashtra, INDIA and Dr. Girish Kulkarni, Director, Department of Technology, Shivaji University, Kolhapur, Maharashtra, INDIA for their valuable suggestions and timely help given to me during this work.

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